MID 1.1: Database for the characterization of the lateral behaviour of infilled frames

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Abstract: The research on infilled reinforced concrete frames is fundamental for the vulnerability assessment of existing buildings. The analysis of the interaction between infill and frame is an open issue in performance-based earthquake engineering, due to its importance in predicting the dynamic behaviour and failure modes of buildings. This study provides an open access database of laboratory tests on masonry infilled reinforced concrete frames, collected from the literature and harmonized in a consistent framework. The data were grouped in categories, to calibrate a piecewise linear curve representing the lateral response of the infill, depending on the masonry wall and the frame details. The gathered data are used to assess analytical models and numerical studies from the literature, with the aim to revise the formulations currently used in the equivalent strut approach. An empirical model for the equivalent strut was developed, through a power-law multiple regression of the database. The open access database in its spreadsheet form is aimed at providing a useful tool for the analysis of infilled reinforced concrete frames.

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1 INTRODUCTION

The importance of masonry infill walls in the seismic performance assessment of reinforced concrete (RC) buildings has been evidenced in past research. Several post-earthquake damage reports allowed to study the role of infill walls in the global behaviour of RC frames (Çelebi et al. 2010; Decanini et al. 2004; Fiore et al. 2012; De Luca et al. 2017; Manfredi et al. 2014; Sezen et al. 2003; Di Trapani et al. 2020; Verderame et al. 2011), even though this aspect is generally neglected in practical design.

The presence of the infill walls influences the seismic demand and the capacity of the structure, at both global and local level. Higher lateral strength and stiffness of infilled RC frames with respect to a "bare" configuration (namely with no infill walls) lead to major changes in the dynamic behaviour and the reduction of the fundamental period generally increases spectral accelerations (e.g. Dolšek and Fajfar 2008; Perrone et al. 2016). Consequently, although the infill walls enhance the strength capacity of the frame, the increase of the global seismic demand may lead to unconservative results

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when analysing the performance of strong infill-weak frame systems. Particularly, early brittle failure of columns with poor shear reinforcement can be caused by the interaction with the infill, reducing the displacement and energy dissipation capacity of the structure.

The correlation between failure modes of the frame and infill walls' properties was evidenced in past studies (Blasi et al. 2018b, 2020; Mehrabi et al. 1996; Pujol and Fick 2010), particularly in the case of existing buildings realized before the introduction of capacity design provisions in modern codes (pre-code buildings in the following) (e.g. Dolšek and Fajfar 2005; De Luca et al. 2014; Perrone et al. 2017). Post-earthquake damage observations and numerical simulations showed brittle failure of gravity load-designed frames caused by the increase of internal forces transferred from the infill to the columns (e.g. Blasi 2019; Ricci et al. 2011; Verderame et al. 2014). Recent building codes and standards (ASCE/SEI 41-17 2017; EN 1998-1 2005; FEMA 356 2000) address the issue of the RC frame-infill interaction by introducing provisions for the additional shear demand in the columns, depending on the lateral strength of the masonry panel.

The RC frame-infill interaction has been widely analysed in recent studies, with the aim of providing suitable numerical or analytical models for the accurate prediction of internal forces in the frame (Cavaleri and Di Trapani 2015; Milanesi et al. 2018; Pantò et al. 2017). The equivalent strut macro-model (Polyakov 1960) is still widely used and various configurations are available in the literature, depending on the number of trusses adopted and their mechanical properties (Chrysostomou et al. 2002; Crisafulli et al. 2005; Varum et al. 2005). The lateral force-displacement (F-d) behaviour of the equivalent strut and its cross-section are generally derived accounting for the properties of both the frame members and masonry infill walls (Bazan and Meli 1980; Liauw and Kwan 1984; Mainstone 1971; Stafford Smith and Carter 1969).

Recent studies evidenced the main shortcomings of the most used formulations for the lateral response of infilled frames, which might fail in predicting the actual collapse mechanism of the frame (Blasi et al. 2018a) or neglect the failure mode of the infill wall in defining its lateral strength (Di Trapani et al. 2018). The development of data-driven approaches based on experimental results is a useful mean to identify the parameters influencing the behaviour of infilled frames and to improve analytical formulations for employment in the engineering practice. A comprehensive analysis of the lateral behaviour of infill walls was conducted by Huang et al. (Huang et al. 2020), by collecting a database of laboratory tests on masonry infilled RC frames. The data were used for multivariate regression analyses, to calibrate empirical formulations for the lateral response of the masonry infill.

This study is aimed at collecting a database of laboratory tests on infilled RC frames, to statistically define the main parameters ruling the lateral behaviour of the masonry wall. An expanded and openly available version of the Masonry Infilled Database, MID 1.0, (De Luca et al. 2016) is developed, considering a wider number of tests to investigate additional statistical and mechanical parameters. The database is called MID 1.1 and includes 134 quasi-static tests on masonry infilled RC portal frames, whose results are analysed in terms of Base-shear-displacement curves.

A piecewise linear approximation of the curves is derived for each test, to calibrate the parameters of a force-displacement model for the infill wall, depending on masonry type and frame properties. The piecewise approximation allows the consideration of additional metadata in MID 1.1, obtaining the monotonic curve of the infill-alone. Furthermore, the ratio between the cracking strength and the maximum strength of the infill wall, as well as its elastic and post-peak softening stiffness are investigated.

The characterization of the load-displacement shape of infilled RC frames, can be useful for seismic assessment methods employing spectrum-based pushover approaches, which include the contribution of the infill walls in the global curve. To this scope, the piecewise curves obtained from the database are compared to numerical pushover curves available in the literature and to analytical models employed in equivalent strut approaches. Lastly, an empirical expression for the definition of the equivalent strut width is derived from the database results, to be used in simplified analyses of infilled RC frames.

The main innovation of the proposed database with respect to similar studies (Huang et al. 2020; Liberatore et al. 2018; De Risi et al. 2018; Šipoš et al. 2013) is the detailed classification of the specimens, depending on both frame and infill properties, the inclusion of additional infill types besides clay hollow bricks and open availability of the data in a usable spreadsheet format.

The results of this work can be useful to improve code-oriented formulations for practical design. Additionally, specific design criteria for infilled RC frames, accounting for different properties of the infill walls, can be used for the design of new buildings. The MID 1.1 is available online as an open access file, which can be continuously updated. Several tools to examine and group the data, depending on the parameters considered in this study, are available in the spreadsheet format.

2 MASONRY INFILL DATABASE MID 1.1

The data are collected in an open access file (De Luca et al. 2020), which includes sections reporting the properties of the specimens and the results of the tests. In addition to the tests data, several features to group and to statistically analyse the results depending on user-defined parameters are included.

The Masonry Infilled Database 1.1 (MID 1.1) was developed by improving the existing MID 1.0 provided by De Luca et al. (2016). The original version of the database mainly includes tests on RC portal frames with clay brick infill walls. Therefore, one of the objectives of MID 1.1 is the inclusion of additional brick types of the infill, such as Aerated Autoclaved Concrete (**AAC**), calcarenite, vitrified ceramic and fly ash bricks. These brick types are indeed increasingly adopted in infill walls, due to their lower thermal transmittance and weight with respect to traditional clay or natural stone bricks.

The main improvement in the MID 1.1 is the classification of the collected tests as function of the frame details (i.e. seismic details, number of floors) and the infill configuration (i.e. brick type, and void ratio of the wall). Different tests types were considered, such as pseudo-static monotonic or cyclic loading and pseudo-dynamic tests. Referring to the specimens, most of the collected data concern single-bay single-storey RC portal frame, with solid infill, whose dimension was mainly full-scaled, half-scaled and one-third-scaled.

The MID1.1 includes data sourced from 24 references, reported in **Table 1**. A total number of 134 tests are collected. The wider variety of infill types in MID 1.1 with respect to MID 1.0 and to most of the databases available in the literature (Liberatore et al. 2018; De Risi et al. 2018; Šipoš et al. 2013) allows a classification of the tests, based on several parameters. Particularly, the infill's brick type is classified as ***CB***: clay bricks, ***CON***: concrete, ***AAC***: autoclaved aerated concrete and ***Other***: calcarenite, vitrified ceramic and fly ash.

A comparison between MID 1.1 and MID 1.0 in terms of number of tests in each category is reported in **Figure 1a**. Despite both versions of the database include the same number of tests on infilled frames with clay brick walls (66), additional tests were collected in MID 1.1 for the remaining categories. Particularly, a specific characterization of ***AAC*** infill walls is allowed, due to the wider number of tests included in MID 1.1.

A comparison of the RC frame details is also provided (**Figure 1b**). The frames are classified as ***SD*** or ***nSD*** (i.e. Seismic Design or no Seismic Design), depending on longitudinal and transverse reinforcement indexes in beams and columns and on the relative beam-to-column resisting moment. Since the experimental campaigns refer to different seismic codes or standards, in the following context "seismic design" should be intended as implementation of seismic detailing according to a code or standard based on capacity design principles. In most cases, this classification reflects a compliance with provisions of Eurocode 8 (EN 1998-1 2005).

2.1 Data sources and classification

The database MID1.1 is composed of different sections, including all the features of the specimens collected. In Section 1: ***SPECIMEN***, details on the geometry of the infilled portal frames are reported, namely number of bays, number of storeys, openings' geometry, type of loading protocol and test scale. As shown in **Figure 2**, most of the collected specimens are single-storey single-bay frames (93%); 11% are two-storey frames, while 7% and 1% are two bays and three bays, respectively. The infill-frame interface was realized using traditional mortar joints for most of the specimens and none of the portal frames featured gap between frame and infill. Haris and Farkas (2018) adopted steel plates embedded in RC members for 12 specimens, while dowel rebars were used for one specimen in (Al-Nimry 2014).

Section 2: ***PANEL***, provides a classification of the infill walls, based on the properties of bricks and mortar joints, such as the presence and the direction of holes in bricks, the brick material, the mortar joints thickness and compressive strength of mortar. **Figure 3a** reports the distribution for infill's opening type. The specimens are classified as ***BARE***, ***SOL***, ***WIN*** or ***DOOR***, namely bare frames, infilled frames with solid infill, infilled frames with window opening and infilled frames with door opening, respectively. Most of the collected tests are referred to infilled frames with solid infill (78%), while 7.5% and 3.7% are infilled with window and door opening respectively.

In **Figure 3b**, the density distribution of the test scale is reported. Most of test are 1/2 or 1/3 scaled specimens (72%), while full-scaled tests represent only 20% of the data. This parameter could be useful to assess if the results collected might be affected by scale effects.

The details on the protocol employed in the collected tests for vertical and lateral loading are provided in **Figure 4a** and **4b**, respectively. For most for the cases, vertical load was directly applied on top of the column and kept constant (***CO***) during the tests. In fewer tests, vertical load was applied to either beams and columns or only beams, while only lateral load was applied in 14 cases. In one case, the detail on the vertical loading protocol are not available in the reference (na). Pseudo-static protocols have been mainly adopted for lateral loading, as shown in **Figure 4b**. The lateral load was applied through cyclic pseudo-static protocol (***C***) in 75% of the tests, while 14% and 11% are monotonic (***M***) pseudo-static or pseudo-dynamic (***P***), respectively.

In **Figure 5**, the density distributions of the aspect ratio, H_w/L_w (H_w = wall height, L_w = wall length), and of the slenderness, t_w/H_w, of the infill wall are provided. The aspect ratio ranges between 0.5 and 0.7 for 56% of the cases, while the minimum and the maximum value are equal to 0.48 and 1.0, respectively. The values collected in the database are consistent with the geometric configuration of the infill walls in typical residential buildings. Infilled RC frames are indeed mostly adopted in residential buildings, where the bay length and the inter-storey height generally range between 3.5 and 7.0 m and between 2.7 m and 4.5 m, respectively (e.g. Polese et al. 2008; Rossetto and Elnashai 2005).

The wall slenderness ratio is within 5.0 and 20.0 for most of the specimens, while the maximum and the minimum value are 4.3 and 40.0, respectively. It is worth evidencing that the wall thickness was not available (na) in the reference for 3.4% of the cases.

One of the main features of the database is the classification of the infill walls based on the brick units. In **Figure 6a** and **6b**, the density distribution of the brick material and the brick type is provided. The brick material is classified as reported in **Figure 1a**, considering four categories, while the brick type is defined based on the presence of holes (***HOLLOW*** or ***SOLID***).

In Mediterranean regions, manufactured bricks are mainly used for structural walls in low-rise masonry buildings and for non-structural applications (infill walls) in RC framed structures. For this reason, hollow clay or concrete units are generally preferred to solid bricks, because of their low weight and thermal conductivity. Solid clay bricks are typically adopted in northern Europe and in United States, where RC framed building are not as common as in Mediterranean regions. On the other hand, solid concrete bricks are widely used in South Asia (Basha and Kaushik 2016; Ganz 2003; De Luca et al. 2019; Salmanpour et al. 2012). **Figure 7** reports the number of specimens with hollow and solid units, in case of concrete and clay bricks. The increasingly attention of the research community to the environment, has encouraged the adoption of novel materials, particularly in construction industry. The use of highly thermally insulating and sustainable materials (AAC, fly ash) in infill walls guarantees a significant reduction of the energy consumption in buildings (Al-Naghi et al. 2020). Considering its spreading, the ***AAC*** category was included in the MID 1.1, aiming to provide useful data for the definition of analytical models.

Referring to the mechanical properties of the bricks, a great variability of the data is observed. The compressive strength ranges between 1.79 and 26.2 MPa, with average equal to 8.47 MPa and coefficient of variation equal to 0.77. Concrete bricks feature significantly higher values (average equal to 13.85 MPa) compared to ***CB***, ***AAC*** and ***Other***, whose average compressive strength was equal to 6.66 MPa, 3.46 MPa and 5.53 MPa, respectively.

The details on the configuration of the RC frames are reported in Section 3: ***FRAME***, including the dimension of the cross sections of the frame members and the mechanical properties of the concrete and the reinforcement steel. In Section 4: ***REINFORCEMENT***, details on longitudinal and transverse reinforcement are provided. The data collected include concrete cover, diameter and number of reinforcement bars and reinforcement index. The information on the reinforcement allows for the specification of the presence of seismic design details in the RC frame.

The density distribution of the reinforcement index for longitudinal and transverse bars in columns are reported in **Figure 8**. According to the main building design codes (ACI 318-14 2014; EN 1992-1-1 2004), the longitudinal reinforcement index in columns ($\rho_{l,col}$) should range between 1% and 8%, while the range of transverse reinforcement index ($\rho_{t,col}$) is not explicitly defined. On the other hand, it is worth assuming a lower limit of $\rho_{t,col}$ equal to 0.4%, based on specific seismic codes provisions on the ductility capacity (EN 1998-1 2005) and on the mechanical properties of concrete and steel, usually adopted for constructions. For most of the collected tests, the longitudinal and transverse reinforcement indexes range between 1% and 3.5% and between 0.5% and 1.5% (**Figure 8**).

Section 5 provides a description of the failure modes (FMs) recorded in the tests, which are classified according to FEMA 306 (1998). Five different categories were defined, namely ***A***, ***B***, ***C***, ***D*** and ***E***, referred to corner crushing, diagonal cracking, sub-panel diagonal cracking, bed joint sliding and RC frame failure, respectively (**Figure 9**).

2.2 Damage state threshold distribution

The correlation between the damage on the infill and the lateral drift of the portal frame, is analysed based on the collected data. The lateral response of the specimens in the database was divided considering two Damage States (DS), namely ***DS2*** and ***DS3***, as suggested in EMS-98 (1998). The ***DS2*** features medium-high damage to the infill, characterized by minor cracking, brittle cladding/plaster falls and mortar joints cracking. The ***DS3*** is characterized by major damage or collapse of the infill, featuring severe cracking paths and collapse of bricks, which cause complete loss of strength of the wall.

The collected data on the failure modes of the infill walls were organized by recording the drift at which ***DS2*** and ***DS3*** were achieved. The density distribution of the data along with the lognormal distribution fit is reported in **Figure 10a** and **b**, for ***DS2*** and ***DS3***, respectively, displaying the median, $\boldsymbol{\eta}$, and the logarithmic standard deviation, $\boldsymbol{\sigma_{log}}$.

The ***DS2*** attainment was not explicitly discussed in some of the collected tests, which mainly focused the ultimate limit state of the analysed portal frames. For most of the available data, the ***DS2*** corresponded to a drift ranging between 0.1-0.4%, with maximum value equal to 1.2%. Referring to ***DS3***, the corresponding drift ranged between 0.3 and 2.5%, while the maximum value recorded was equal to 5%. The high values of $\boldsymbol{\sigma}$ evidence the uncertainty in the failure mode prediction, due to the influence of several parameters, as relative infill-to-frame stiffness and mechanical properties of bricks and mortar joints. The results obtained are consistent to the observations provided from recent studies focused on the damage assessment of RC buildings with hollow clay infill walls (Ricci et al. 2016; De Risi et al. 2018).

It is worth mentioning that several references did not explicitly address the attainment of a specific damage state, hindering a reliable comparison between solid infilled frames and infilled frames with openings. Additionally, a similar variability is obtained grouping the data depending on the brick type. On the other hand, being this study aimed at characterizing the shape of the load-displacement behaviour of infilled frames regardless of the failure modes, these details are not required in the following.

2.3 Piecewise linear fit of lateral backbones curves

The force-displacement envelope curves obtained in the collected tests were approximated through a piece-wise linear fitting. The approximation procedure was developed by De Luca et al. (2013) and it is aimed at deriving, from the original curve, a multilinear behaviour, composed of four branches. A linear fit example is reported in (**Figure 11**). The grey and black solid lines are referred to the multi-linearization and the original curve, respectively.

The first stage of the curve represents the elastic response of the system, up to the attainment of the cracking strength of the infill, $\boldsymbol{F_{cr}}$. The second post-cracking slope represents the generation of the strut mechanism in the wall, when lateral stiffness reduces due to the development of cracks in the infill. The post-cracking slope ends at the attainment of the peak strength, $\boldsymbol{F_m}$, which is followed by two softening slopes, representing the degradation due to progressive increase of damage in the infill. Since the backbone curve is calibrated based on both monotonic and cyclic tests, the softening slopes refer to both in-cycle and cyclic degradation. Therefore, the piecewise model obtained is suitable for indirect modelling of the cyclic behaviour of infilled RC frames, according to NIST GCR 10-917-5 (Deierlein et al. 2010).

In the Section ***Piecewise linear fit*** of MID1.1, the load-displacement coordinates defining the multi-linear fit of each experimental curve are provided. The second softening slope is not included within the piecewise curves' data in the database, since $\boldsymbol{K_{soft2}}$ was either slightly lower than $\boldsymbol{K_{soft}}$ or close to zero for most of the considered tests. For this reason, three-linear curves featuring elastic, post-cracking and softening stiffness equal to K_1, K_2 and K_{soft}, respectively, are provided in the database.

It is worth mentioning that the cyclic response of infilled RC frames may be significantly uneven in positive and negative direction, therefore the 134 curves fitted correspond to the average response in case of cyclic tests.

The force and displacement values in the obtained multi-linear curves are normalized to the peak strength, F_m, and to the corresponding displacement, D_m, respectively, aiming to obtain non-dimensional parameters ruling the shape of each curve. One of the objectives of this study is the estimation of the ratio between the maximum strength, F_m, and the cracking strength, F_{cr}, (overstrength ratio), whose values could be directly compared through the normalization described above.

In the section ***Piecewise_Global*** of the database, all the normalized curves are reported. The tests were grouped in different categories, based on the properties of the reinforced concrete members and the masonry infill. The frames are defined as ***SD*** and ***nSD***, namely conforming and non-conforming to seismic design criteria, respectively. The infill walls were grouped according to two different classifications, considering the brick type and the brick material, respectively. Referring to the brick type, the infill was classified as ***H*** (Hollow bricks) or ***S*** (solid bricks), while four brick material categories were defined, namely clay brick (***CB***), concrete (***CON***), autoclaved aerated concrete (***AAC***) and other material (***Other***).

For each considered category, the median curve, η, along with the curves referred to 16th and 84th percentiles (P_{16} and P_{84}, respectively) were computed, aiming to identify the variation range of three parameters, namely the ratio between K_2/K_1, K_{soft}/K_1, and F_m/F_{cr}. The density distribution of the values of each considered parameter was fitted through a log-normal probability density function. A truncated distribution was assumed for the F_m/F_{cr} data, since the values lower than 1.0 are not consistent with the definition of the ratio, while in the case of K_2/K_1, an upper limit equal to one was assumed. Referring to K_{soft}/K_1, a standard log-normal function was used.

In **Figure 12**, the comparison of the normalized curves is provided, considering four categories, namely ***CB***, ***CON***, ***AAC*** and ***Other***. The values of η, σ_{log}, P_{16} and P_{84}, obtained for the backbone parameters, F_m/F_{cr}, K_2/K_1 and K_{soft}/K_1, are reported **Table 2**, for each category considered.

A great variability of the results was observed for all the considered parameters, particularly referring to the post peak response of the infilled frame. The value of K_{soft}/K_1 ranges between 0.00 and 0.57 when considering all the 134 tests and no correlation with the infill's and frame's type is observed. It is worth noting that the η and P_{16} values obtained for K_{soft}/K_1 are close to 0.00 (e.g. the lower bound of the log-normal distribution) for all the considered categories. The global post peak behaviour is indeed highly influenced by the post-yielding slope of the RC frame, which features either horizontal perfectly-plastic or hardening slope, both in case of ***SD*** and ***nSD***. Hence, the softening stage is characterized by a significantly higher amount of dissipated energy, with respect to the previous stages. An additional contribution to the dissipated energy is produced by mortar joint frictional sliding (Mehrabi et al. 1996). On the other hand, the mechanical properties of the bricks are less influent, since they are often subjected to rigid body modes in this stage.

Referring to $\boldsymbol{F_m/F_{cr}}$ and $\boldsymbol{K_2/K_1}$, a lower scatter of the results is observed compared to $\boldsymbol{K_{soft}/K_1}$. The value of $\boldsymbol{F_m/F_{cr}}$ ranges between 1.05 and 5.73 when considering all the 134 tests and higher values were obtained for ***CB*** and ***CON*** with respect to ***AAC*** and ***Other***.

Table 2 shows a negligible influence of the brick type on the median $\boldsymbol{F_m/F_{cr}}$, when including all brick materials. On the other hand, a significantly different trend is observed analysing data referred to a specific brick material. In case of clay bricks, the median $\boldsymbol{F_m/F_{cr}}$ rises from 1.56, in ***H-CB***, to 1.92, in ***S-CB*** (**Figure 13**). The opposite trend was obtained for the case of concrete bricks, where the median $\boldsymbol{F_m/F_{cr}}$ is equal to 1.56 and 1.85 for ***S-CON*** and ***H-CON***, respectively. This result confirms the need of accounting for both brick type and brick material when defining the backbone F-d curve of infilled frames and highlights the utility of the proposed database.

Considering the frame type, no noticeable influence is observed for $\boldsymbol{K_2/K_1}$, while lower overstrength values were obtained in case of ***SD*** with respect to ***nSD***. It is worth mentioning that the onset of damage in the infill generally occurs far below the elastic limit of the frame members, therefore, the reinforcement details have less influence on the results. On the other hand, ***SD*** frames might feature stiffer columns compared to ***nSD***, to comply capacity design requirements, leading to a reduction of the internal forces in the infill during lateral loading and, consequently, raising the cracking limit value in the global response.

A similar analysis of the backbone parameters was conducted by De Risi et al. (2018), even though the data were not grouped in different categories. The results obtained in (De Risi et al. 2018) for $\boldsymbol{F_m/F_{cr}}$ are consistent to those provided in this work, while a significant difference is observed referring to $\boldsymbol{K_2/K_1}$ and $\boldsymbol{K_{soft}/K_1}$. This feature confirms the high uncertainty in characterizing of the post-cracking and softening stage in infilled RC frames.

2.4 Infill wall response

In numerical and analytical studies, the equivalent strut formulation is a widely adopted method to assess the influence of the infill walls on the seismic response of RC buildings, both at global and local level. Referring to local interaction studies, complex modelling approaches have been recently adopted (Blasi et al. 2018a; Jeon et al. 2015; Redmond et al. 2018), to assess the reliability of existing analytical formulation in predicting the influence of the infill walls on the failure mode of the frames. An accurate estimation of the lateral response of the infill is indeed fundamental for the local interaction assessment.

Based on the piece-wise linear curves obtained in this work, the lateral force-displacement behaviour of the infill-alone was derived according to the approach by Blasi et al. (2018a). Firstly, the lateral response of the RC frame was defined, considering a bilinear hardening model, with yielding strength $\boldsymbol{V_y} = 4\boldsymbol{M_y}/\boldsymbol{h_c}$ and ultimate strength $\boldsymbol{V_u} = 4\boldsymbol{M_u}/\boldsymbol{h_c}$, where $\boldsymbol{M_y}$,

$\boldsymbol{M_u}$ and $\boldsymbol{h_c}$ are the yielding moment, the ultimate resisting moment and the height of the column, respectively. The yielding displacement, $\boldsymbol{D_y}$, and the ultimate displacement, $\boldsymbol{D_u}$, were calculated according to Eurocode 8 Part 3 (2005).

The obtained bilinear curve of the RC frame was subtracted to the piece-wise curve referred to the infill+frame system (Global response), to obtain the lateral behaviour of the infill-alone, as illustrated in **Figure 14**. As for the global backbone curves, the infill-alone curve was normalized to the maximum lateral strength, $\boldsymbol{F_{m,w}}$, and to the corresponding displacement, $\boldsymbol{D_{m,w}}$.

In the section ***Piecewise_wall*** of the database, all the normalized curves referred to the infill-alone response are reported. As for the section ***Piecewise_Global***, the tests were grouped in different categories, namely, frame type, brick type and brick material.

In **Figure 15**, the normalized curves obtained for the infill-alone are provided, including the 16^{th}, 50^{th} and 84^{th} percentiles. The categories considered in **Figure 15** are the same as those in **Figure 12**, allowing to compare the response of the global curve to that of the infill-alone.

The obtained values of the normalized parameters are provided in **Table 3**. As for the global response, a significant variability of the results was observed for all the considered parameters. The value of $\boldsymbol{K_{soft,w}/K_{1,w}}$ ranges between 0.00 and 0.77 and is unrelated to the brick type or the brick material. A lower $\boldsymbol{\sigma_{log}}$ and, consequently, a tighter $\boldsymbol{P_{16}\text{-}P_{84}}$ range is observed in case of ***Other***, caused by the few available results.

A lower variability was obtained in the case of $\boldsymbol{F_{m,w}/F_{cr,w}}$, which ranges between 1.02 and 6.12. As for the global response, higher values were obtained for ***CB*** and ***CON*** with respect to ***AAC*** and ***Other***. It is worth observing that the average values of $\boldsymbol{F_{m,w}/F_{cr,w}}$ are lower than those related to the global response, confirming that the maximum strength is generally achieved prior the yielding of the frame.

For almost all the considered tests, the analytical value of $\boldsymbol{D_y}$ was indeed significantly higher than the cracking displacement $\boldsymbol{D_{cr}}$ and the frame failure (either flexural or shear) occurred after the achievement of $\boldsymbol{D_m}$. Consequently, a neglectable influence of the frame design on $\boldsymbol{F_{m,w}/F_{cr,w}}$ and $\boldsymbol{K_{2,w}/K_{1,w}}$ is observed comparing ***SD*** to ***nSD***, in contrast to the infill+frame results. On the other hand, a correlation between the brick type and material and the ratio $\boldsymbol{K_{2,w}/K_{1,w}}$ is observed; higher values were obtained for hollow bricks and in case of ***CB*** and ***CON***.

According to the observed results, the influence of the frame type and the brick type on the analysed parameters is negligible, while the brick material and, consequently, its mechanical properties, is highly influent, particularly referring to $\boldsymbol{F_{m,w}/F_{cr,w}}$.

3 COMPARISON WITH EMPIRICAL MODELS AND NUMERICAL STUDIES

Recent spectrum-based methods for seismic risk assessment require the definition of static pushover curves referred to a single-degree-of-freedom (SDOF) model, representing the building under investigation and including the effect of the infill walls (Borzi et al. 2008; Dolšek and Fajfar 2004; Del Gaudio et al. 2015; De Luca et al. 2014). In regional scale analyses, the damage state bounds of a building are derived from SDOF pushover curves, which should be representative of the structural features of each archetype in the building taxonomy. Therefore, an accurate characterization of the load-displacement response of the structural system is required. In the case of infilled frames, the correct evaluation of the lateral response of the masonry wall is fundamental for the prediction of brittle failure modes in the frame members caused by the local interaction with the infill (Blasi et al. 2018a; Jeon et al. 2015).

The database results allow to define a characteristic piecewise linear shape for each infilled frame type considered, aiming to improve the effectiveness of spectrum-based pushover analyses. To this scope, a comparison between the global curves obtained from the database and numerical pushover curves obtained from the literature studies, developed with high-fidelity numerical models, is proposed. Additionally, the values of $F_{m,w}/F_{cr,w}$, $K_{2,w}/K_{1,w}$ and $K_{soft,w}/K_{1,w}$ suggested in six simplified analytical models available in the literature are compared to those obtained from the MID 1.1, aiming to identify possible improvements based on the parameters analysed in this work.

3.1 Global piece-wise monotonic backbone – comparison with numerical pushover curves

The static pushover analyses selected from the literature are referred to the studies reported in **Table 4**. The RC infilled frames analysed were classified depending on the design of the RC members (***SD*** and ***nSD***) and on the material and type of infill walls. The same nomenclature introduced in chapter 2 is used in **Table 4**. The piecewise linear fit of each pushover curve was obtained according to the same procedure described in section 2.3, and the Force-displacement coordinates were normalized to the maximum strength and to the relative displacement, respectively.

It is worth mentioning that almost all the collected numerical studies analysed gravity load-designed frames with hollow clay brick infill, confirming its wide adoption in RC buildings. As a matter of fact, the vulnerability assessment of seismic designed frames with masonry infill is less relevant, since structural damage due to the presence of the infill is generally observed in pre-code buildings. For this reason, most of the past and current studies dealing with the influence of the infill on the seismic performance of the structures, focus on gravity load designed (or non-seismic) frames.

On the other hand, the accurate evaluation of the properties of the infill walls and, consequently, the improvement of existing models defining their lateral response, can be used for code-oriented formulations aimed at considering the infill alongside the frame members as auxiliary lateral load resisting system in modern RC buildings. The comparison between the numerical curves collected from the literature and those in the database is reported in **Figure 16**.

According to the available results of the database, four categories are compared, namely ***nSD-H-CB***, ***SD-H-CB***, ***S-CB*** and ***AAC***. The curves P_{16}-P_{84} and η, referred to the database, are represented with dashed and solid black lines, respectively. ***S-CB*** includes both ***nSD*** and ***SD*** frames, while ***AAC*** includes ***Hollow***, ***Solid***, ***nSD*** and ***SD***, since fewer results were available within these categories comparing to hollow clay bricks. Most of the capacity curves collected are outside the range P_{16}-P_{84}, particularly referring to the softening slope in case of ***nSD-H-CB***. The ratio F_m/F_{cr} is significantly underestimated with respect to the database results in the case of ***S-CB***, while higher values were obtained considering ***AAC*** category.

A fair correspondence between the curves was only observed in the case of ***SD-H-CB***, for which the ratio $F_{m,w}/F_{cr,w}$ is close to the average result from the database and the post-peak slope is approximately within the range P_{16}-P_{84}. Since the post-peak response of the infill is generally assumed empirically, due to its uncertain estimation, the high scatter observed is consistent with the considerations above. In the case of ***AAC*** walls, a lower normalized elastic stiffness is observed comparing the numerical curves to the database results. This feature is probably related to the modelling assumptions in the numerical study (Šipoš et al. 2018), which neglected the variability of $F_{m,w}/F_{cr,w}$ and $K_{2,w}/K_{1,w}$ depending on the brick material.

The results obtained show that the assumption of accurately-calibrated parameters for the lateral response of the infill, can highly influence the results of numerical analyses. The contribution of the present study to the definition of *ad-hoc* formulations, depending on the infill and on the frame type, can enhance the accuracy of the numerical analyses focused on the local interaction and global performances of infilled RC buildings.

3.2 Infill piece-wise monotonic backbone – comparison with consolidated analytical models

Aiming to assess the reliability of existing formulations used to define the lateral response of the infill walls, the normalized curves obtained for each test in the database were compared to six models available in the literature. In the considered models, the backbone parameters, $F_{m,w}/F_{cr,w}$, $K_{2,w}/K_{1,w}$ and $K_{soft,w}/K_{1,w}$, are either defined empirically or through simplified formulations, accounting for several properties of both infill wall and frame members. Therefore, in case of missing specimens' details due to lack of information in the reference, the comparison with some of the literature models was not possible.

It is worth mentioning that the model by Burton and Deierlein (2013) was developed for simulating the response of Californian RC buildings designed according to engineering practice in the early 20th century and, consequently, it is not meant to represent all the possible infilled frames configurations. Additionally, the model does not account for the influence of the infill's properties, since all the backbone parameters were defined statistically, based on laboratory tests from the literature. The same considerations apply for $F_{m,w}/F_{cr,w}$, and $K_{soft,w}/K_{1,w}$ referred to the model by Panagiotakos and Fardis (1996).

The average values of $F_{m,w}/F_{cr,w}$, $K_{2,w}/K_{1,w}$ and $K_{soft,w}/K_{1,w}$, obtained for each brick material using the literature models, are provided in **Table 5**. In case of ***AAC*** bricks, the evaluation of the backbone parameters was not possible for five out of six models considered, due to lack of details in several references. Additionally, the model provided by Di Trapani et al. (2018) only allows to calculate $K_{soft,w}/K_{1,w}$, since the lateral response of the infill is simulated through a parabolic curve with linear tension softening.

In **Figure 17**, the average values of the backbone parameters, calculated using the models from the literature, are compared to the database results, for each brick material category. Referring to $F_{m,w}/F_{cr,w}$, a fair correspondence between the database and the literature results is observed, for all the models considered. On the other hand, most of the considered literature models give unconservative values for ***CB*** and ***CON*** in case of local interaction assessment, except for the model by Stavridis et al. (2017). In fact, the predicted $F_{m,w}/F_{cr,w}$ according to the analytical models is lower than the median values calculated from the database. According to Blasi et al. (2018a), the underestimation of $F_{m,w}/F_{cr,w}$ might hinder the detection of brittle failure of the columns due to the interaction with the infill, which is a major issue in case of pre-code buildings.

Referring to $K_{2,w}/K_{1,w}$, the analytical model results for ***CB*** and ***CON*** fall within the P_{16}-P_{84} range, even though a high dispersion in the database was obtained. On the contrary, a lower scatter is observed in case of ***Other***, for which the models' results are significantly higher comparing to the database.

Despite the high uncertainty in the evaluation of $K_{soft,w}/K_{1,w}$, a good agreement between the database and the analytical results is observed. Except for the case of ***Other***, all the analytical values are close to the median calculated among the database.

3.3 Empirical model for the equivalent strut width

In equivalent strut methods, the lateral behaviour of the infill is generally computed depending on theoretical formulations expressing the initial and the secant stiffness, K_1 and K_{sec}, respectively. The value of K_1 is equal to the shear stiffness of the uncracked wall (equation (1), while K_{sec} represents the axial stiffness of the post-cracking truss mechanism (equation (2).

$$K_1 = \frac{G_w t_w L_w}{H_w} \tag{1}$$

$$K_{sec} = \frac{E_w b_w t_w}{d_w} \tag{2}$$

In equations (1) and (2), E_w and G_w are the elastic and the shear modulus of the masonry prism, respectively, while b_w is the width of the equivalent strut, generally calculated depending on the properties of both frame and infill (Stafford Smith and Carter 1969). Nevertheless, b_w is affected by several parameters and its accurate evaluation using theoretical models can be challenging, leading to uncertainty in calculating K_{sec}.

Aiming to overcome this issue, a data-driven formulation expressing the width of the equivalent strut model, to be used for simplified analyses of infilled frames, is proposed. Firstly, the value of the strut width, b_w, was calculated for each infill-alone piecewise linear curve derived from the database, using equation (3).

$$b_w = \frac{K_{sec} d_w}{E_w t_w} \tag{3}$$

A multiple power-law regression of the b_w data was performed, on the basis of three predictors, namely the angle of the diagonal of the infill with respect to the horizontal direction, θ_w, the elastic modulus, E_w and the relative infill-to-frame stiffness, λ_w, evaluated according to Stafford Smith and Carter (1969).

The equation adopted for the predicted value of the strut width, $b_{w,p}$, has the form:

$$b_{w,p}(\theta_w, E_w, \lambda_w) = e^{\beta_0} \cdot \theta_w^{\beta_1} \cdot E_w^{\beta_2} \cdot \lambda_w^{\beta_3} \tag{4}$$

where $b_{w,p}$ and E_w are expressed in mm and MPa, respectively. The power-law regression parameters, β_i, in equation (4), were calibrated though the minimization of the sum of squared residuals. The procedure required a logarithmic transformation of equation (4), to calculate the residuals, ε_i, referred to each observed value of the strut width, $b_{w,i}$, according to equation (5):

$$\varepsilon_i = ln(b_{w,i}) - ln(b_{w,p,i}) = ln(b_{w,i}) - \beta_0 + \beta_1 \, ln\, \theta_{w,i} + \beta_2 \, ln\, E_{w,i} + \beta_3 \, ln\, \lambda_{w,i} \tag{5}$$

The sum of squared residuals was defined as:

$$\sum_{i=1}^{n} {\varepsilon_i}^2 = [\boldsymbol{\varepsilon}]^{\boldsymbol{T}} \cdot [\boldsymbol{\varepsilon}] = ([\boldsymbol{Y}] - [\boldsymbol{X}][\boldsymbol{\beta}])^T ([\boldsymbol{Y}] - [\boldsymbol{X}][\boldsymbol{\beta}]) \tag{6}$$

In equation (6), $[\varepsilon]$, $[Y]$, $[X]$, and $[\beta]$ are the matrices including the residuals, the values of the observed $b_{w,i}$, the predictors and the regression parameters, respectively, while n is the number of data collected.

Aiming to provide a formulation depending on the brick material, two sets of power-law regression parameters to be used in equation (4) were derived (**Table 6**), referred to clay bricks infill and concrete bricks infill. An additional set (ALL) derived from all the data was also included. The regression was not performed for ***AAC*** and ***Other***, due to insufficiency of records available to obtain a suitable regression.

Figure 18 reports comparisons between the observed and the predicted values of the strut width, calculated using the developed empirical equations. The coefficients of determination, R^2, obtained do not indicate a high accuracy of the model in predicting the observed values of b_w, due to the great dispersion of the data. On the other hand, the uncertainty of the estimation is consistent with the results of similar studies on data-driven models (Huang et al. 2020). The wide number of parameters influencing the post-cracking behaviour of the infill cause challenges in the definition of accurate equation for the evaluation of the strut width. For this reason, the regression of laboratory test data represents a reliable alternative to simplified theoretical models, which might be too succinct or inconsistent with the experimental findings.

4 CONCLUSIONS

The tests collected in this work were accurately selected among the literature studies on infilled frames, to obtain a comprehensive analysis of the infill wall's behaviour depending on several parameters, related to both masonry wall and frame members. The database entirely regards reinforced concrete frames with unreinforced masonry infill and purposely neglects other categories, to avoid major dispersion of the data.

The envelope of the experimental load-displacement response of the infilled frame is approximated through a piece-wise linear model, whose characterization was analysed depending on the brick material, the brick type and the frame type. A significant influence of the brick material on the ratio between the cracking strength and the maximum lateral strength in the piecewise curve is observed. On the other hand, the post-peak slope seems not clearly related to the considered parameters.

The evaluation of the response of the infill-alone by subtracting the lateral behaviour of the reinforced concrete frame to the curve referred to the whole system allows to focus on the masonry wall's parameters and confirms the correlation between the brick material and the ratio between the peak and the cracking strength.

The results of numerical pushover studies on reinforced concrete buildings are assessed by comparing the parameters characterizing the pushover curve to the database results. For all the considered parameters, a significant difference between the numerical and the database results is observed. Moreover, six widely adopted analytical models are revised based on the database results. Despite the considered models are suitable in approximating of the load-displacement response of infilled frames, the influence of the brick material on the ratio between the peak to cracking strength is generally neglected. This feature can cause underestimation of the maximum strength and leads to unconservative results when analysing the failure of the columns due to the interaction with the infill.

The median values of the overstrength provided in this study, calculated among the data collected for each brick material, could represent a suitable improvement to existing formulations. Additionally, the empirical model calibrated through power law multiple regression of the data can be used in simplified analyses of infilled frames for the calibration of the equivalent strut, depending on the brick material.

The database developed herein is meant to provide comprehensive information for the research on infilled RC frames. The accurate analysis of the interaction between masonry infill and reinforced concrete frames is fundamental for the vulnerability assessment of existing buildings and is strictly related to the reliability in the definition of the lateral behaviour of the infill. Furthermore, the results presented in this work can be used to develop suitable code-oriented formulations, to be adopted for the design of new buildings.

DATA AVAILABILITY STATEMENT

All data used during the study, including the Excel spreadsheet file of the Masonry Infill Database MID 1.1, are available at the University of Bristol data repository, data.bris, at https://doi.org/10.5523/bris.71oex4uyxye925b8fai0v1qk5, in accordance with funder data retention policies.

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